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IN THE U.S. PATENT AND TRADEMARK OFFICE

BEFORE THE BOARD OF APPEALS AND INTERFERENCES

Inventor	Roger E LO
Patent App.	10/511,865
Filed	10 March 2005
For	METHOD FOR PRODUCING CRYOGENIC SOLID MONOPROPELLANTS .....

Art Unit   1793   Examiner Mc Donough, J

Hon. Commissioner of Patents
Box 1450
Alexandria, VA 22313-1450

SUPPLEMENT TO APPEAL BRIEF UNDER 37 CFR 41.37

Appellants are filing this Supplement to Appeal Brief in response to the Board's communication mailed 26 September 2009.

Appellants are attaching

1. http://en.wikipedia.org/wiki/Rocket_propellant and

2. http://en.wikipedia.org/wiki/Explosive.

Appellants inadvertently failed to attach these two documents to the Evidence Appendix of their Appeal Brief filed 10 February 2009. Appellants' undersigned representative apologizes to the Board and to the Examiner for failing to attach copies of

these documents to the Evidence Appendix.

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Enclosures:

1. http://en.wikipedia.org/wiki/Rocket_propellant and
2. http://en.wikipedia.org/wiki/Explosive.

23095
Ser. No.
10/511, 865

Rocket propellant

From Wikipedia, the free encyclopedia

Rocket propellant is mass that is stored, usually in some form of propellant tank, prior to being used as the propulsive mass that is ejected from a rocket engine in the form of a fluid jet to produce thrust.

Chemical rocket propellants are most commonly used, which undergo exothermic chemical reactions which produce hot gas which is used by a rocket for propulsive purposes.

Contents

Overview

Rockets create thrust by expeling mass backwards in a high speed jet (see *Newton's Third Law*). Chemical rockets, the subject of this article, create thrust by reacting propellants into very hot gas, which then expands and accelerates within a nozzle out the back. The amount of the resulting forward force, known as thrust, that is produced is the mass flow rate of the propellants multiplied by their exhaust velocity (relative to the rocket), as specified by Newton's third law of motion. Thrust is therefore the equal and opposite reaction that moves the rocket, and not any interaction of the exhaust stream with air around the rocket (but see base bleed).

The Space Shuttle Atlantis during takeoff

Equivalently, one can think of a rocket being accelerated upwards by the pressure of the combusting gases in the combustion chamber and nozzle. This operational principle stands in contrast to the commonly held assumption that a rocket "pushes" against the air behind or below it. Rockets in fact perform better in space (where there is in theory nothing behind or beneath them to push against), because they do not need to overcome air resistance and atmospheric pressure on the outside of the nozzle.

The maximum velocity that a rocket can attain in the absence of any external forces is primarily a function of its mass ratio and its *exhaust velocity*. The relationship is described by the *rocket equation*: $V_f = V_e \ln(M_0 / M_f)$. The mass ratio is just a way to express what proportion of the rocket is fuel when it starts accelerating. Typically, a single-stage rocket might have a mass fraction of 90% propellant, which is a mass ratio of 1/(1-0.9) = 10. The exhaust velocity is often reported as *specific*

impulse.

The first stage will usually use high-density (low volume) propellants to reduce the area exposed to atmospheric drag and because of the lighter tankage and higher thrust/weight ratios. Thus, the Apollo-Saturn V first stage used kerosene-liquid oxygen rather than the liquid hydrogen-liquid oxygen used on the upper stages (hydrogen is highly energetic per kilogram, but not per cubic metre). Similarly, the Space Shuttle uses high-thrust, high-density SRBs for its lift-off with the liquid hydrogen-liquid oxygen SSMEs used partly for lift-off but primarily for orbital insertion.

Chemical propellants

There are three main types of propellants: solid, liquid, and hybrid.

Solid propellants

The earliest rockets were created hundreds of years ago by the Chinese, and were used primarily for fireworks displays and as weapons. They were fueled with black powder, a type of gunpowder consisting of a mixture of charcoal, sulfur and potassium nitrate (saltpeter). Rocket propellant technology did not advance until the end of the 19th century, by which time smokeless powder had been developed, originally for use in firearms and artillery pieces. Smokeless powders and related compounds have seen use as double-base propellants.

Solid propellants (and almost all rocket propellants) consist of an oxidizer and a fuel. In the case of gunpowder, the fuel is charcoal, the oxidizer is potassium nitrate, and sulfur serves as a catalyst. (Note: sulfur is not a true catalyst in gunpowder as it is consumed to a great extent into a variety of reaction products such as K_2S. The sulfur acts mainly as a sensitizer lowering threshold of ignition.) During the 1950s and 60s researchers in the United States developed what is now the standard high-energy solid rocket fuel. The mixture is primarily ammonium perchlorate powder (an oxidizer), combined with fine aluminium powder (a fuel), held together in a base of PBAN or HTPB (rubber-like fuels). The mixture is formed as a liquid, and then cast into the correct shape and cured into a rubbery solid. Solid fueled rockets are much easier to store and handle than liquid fueled rockets, which makes them ideal for military applications. In the 1970s and 1980s the U.S. switched entirely to solid-fuelled ICBMs: the LGM-30 Minuteman and LG-118A Peacekeeper (MX). In the 1980s and 1990s, the USSR/Russia also deployed solid-fuelled ICBMs (RT-23, RT-2PM, and RT-2UTTH), but retains two liquid-fuelled ICBMs (R-36 and UR-100N). All solid-fuelled ICBMs on both sides have three initial solid stages and a precision maneuverable liquid-fuelled bus (http://www.boeing.com/defense-space/space/propul/peacekpr.html) used to fine tune the trajectory of the reentry vehicle.

Their simplicity also makes solid rockets a good choice whenever large amounts of thrust are needed and cost is an issue. The Space Shuttle and many other orbital launch vehicles use solid fuelled rockets in their first stages (solid rocket boosters) for this reason.

However, solid rockets have a number of disadvantages relative to liquid fuel rockets. Solid rockets have a lower specific impulse than liquid fueled rockets. It is also difficult to build a large mass ratio solid rocket because almost the entire rocket is the combustion chamber, and must be built to withstand the high combustion pressures. If a solid rocket is used to go all the way to orbit, the payload fraction is very small. (For example, the Orbital Sciences Pegasus rocket is an air-launched three-stage solid rocket orbital booster. Launch mass is 23,130 kg, low earth orbit payload is 443 kg, for a payload fraction of 1.9%. Compare to a Delta IV Medium, 249,500 kg, payload 8600 kg, payload fraction 3.4% without air-launch assistance.)

A drawback to solid rockets is that they cannot be throttled in real time, although a predesigned thrust schedule can be built into the grain during manufacture.

Solid rockets can often be shut down before they run out of fuel. Essentially, the rocket is vented or an extinguishant injected so as to terminate the combustion process. In some cases termination destroys the rocket, and then this is typically only done by a Range Safety Officer if the rocket goes awry. The third stages of the Minuteman and MX rockets have precision shutdown ports which, when opened, reduce the chamber pressure so abruptly that the interior flame is blown out. This allows a more precise trajectory which improves targeting accuracy.

Finally, casting very large single-grain rocket motors has proved to be a very tricky business. Defects in the grain can cause explosions during the burn, and these explosions can increase the burning propellant surface enough to cause a runaway pressure increase, until the case fails.

Liquid propellants

Liquid fueled rockets have better specific impulse than solid rockets and are capable of being throttled, shut down, and restarted. Only the combustion chamber of a liquid fueled rocket needs to withstand combustion pressures and temperatures. On vehicles employing turbopumps, the fuel tanks carry very much less pressure and thus can be built far more lightly, permitting a larger mass ratio. For these reasons, most orbital launch vehicles and all first- and second-generation ICBMs use liquid fuels for most of their velocity gain.

The primary performance advantage of liquid propellants is the oxidizer. Several practical liquid oxidizers (liquid oxygen, nitrogen tetroxide, and hydrogen peroxide) are available which have much better specific impulse than ammonium perchlorate when paired with comparable fuels.

Most liquid propellants are also cheaper than solid propellants. For orbital launchers, the cost savings do not, and historically have not mattered; the cost of fuel is a very small portion of the overall cost of the rocket, even in the case of solid fuel.

The main difficulties with liquid propellants are also with the oxidizers. These are generally at least moderately difficult to store and handle, either due to extreme toxicity (nitric acids), moderately cryogenic (liquid oxygen), or both (liquid fluorine is a perennial favorite of wild-eyed enthusiasts). Several exotic oxidizers have been proposed: liquid ozone (O_3), ClF_3, and ClF_5, all of which are unstable, energetic, and toxic.

Liquid fuelled rockets also require potentially troublesome valves and seals and thermally stressed combustion chambers, which increase the cost of the rocket. Many employ specially designed turbopumps which raise the cost enormously due to difficult fluid flow patterns that exist within the casings.

Though all the early rocket theorists proposed liquid hydrogen and liquid oxygen as propellants, the first liquid-fueled rocket, launched by Robert Goddard on March 16, 1926, used gasoline and liquid oxygen. Liquid hydrogen was first used by the engines designed by Pratt and Whitney for the Lockheed CL-400 Suntan reconnaissance aircraft in the mid-1950s. In the mid-1960s, the Centaur and Saturn upper stages were both using liquid hydrogen and liquid oxygen.

The highest specific impulse chemistry ever test-fired in a rocket engine was lithium and fluorine, with hydrogen added to improve the exhaust thermodynamics (making this a tripropellant)[1]. The combination delivered 542 seconds (5.32 kN·s/kg, 5320 m/s) specific impulse in a vacuum. The

impracticality of this chemistry highlights why exotic propellants are not actually used: to make all three components liquids, the hydrogen must be kept below -252 °C (just 21 K) and the lithium must be kept above 180 °C (453 K). Lithium and fluorine are both extremely corrosive, lithium ignites on contact with air, fluorine ignites on contact with most fuels, and hydrogen, while not hypergolic, is an explosive hazard. Fluorine and the hydrogen fluoride (HF) in the exhaust are very toxic, which damages the environment, makes work around the launch pad difficult, and makes getting a launch license that much more difficult. The rocket exhaust is also ionized, which would interfere with radio communication with the rocket.

The common liquid propellant combinations in use today:

- LOX and kerosene (RP-1). Used for the lower stages of most Russian and Chinese boosters, the first stages of the Saturn V and Atlas V, and all stages of the developmental Falcon 1 and Falcon 9. Very similar to Robert Goddard's first rocket. This combination is widely regarded as the most practical for civilian orbital launchers.

- LOX and liquid hydrogen, used in the Space Shuttle, the Centaur upper stage, the newer Delta IV rocket, the H2A rocket, and most stages of the European Ariane rockets.

- Nitrogen tetroxide (N_2O_4) and hydrazine (N_2H_4), MMH, or UDMH. Used in military, orbital and deep space rockets, because both liquids are storable for long periods at reasonable temperatures and pressures. This combination is hypergolic, making for attractively simple ignition sequences. The major inconvenience is that these propellants are highly toxic, hence they require careful handling. Hydrazine also decomposes energetically to nitrogen and hydrogen, making it a fairly good monopropellant.

Gas Propellants

A gas propellant, usually involves some sort of compressed gas. However due to the low density and high weight of the pressure vessel, gases see little current use.

Hybrid propellants

A hybrid rocket usually has a solid fuel and a liquid or gas oxidizer. The fluid oxidizer can make it possible to throttle and restart the motor just like a liquid fuelled rocket. Hybrid rockets are also cleaner than solid rockets because practical high-performance solid-phase oxidizers all contain chlorine, versus the more benign liquid oxygen or nitrous oxide used in hybrids. Because just one propellant is a fluid, hybrids are simpler than liquid rockets.

Hybrid motors suffer two major drawbacks. The first, shared with solid rocket motors, is that the casing around the fuel grain must be built to withstand full combustion pressure and often extreme temperatures as well. However, modern composite structures handle this problem well, and when used with nitrous oxide or hydrogen peroxide relatively small percentage of fuel is needed anyway, so the combustion chamber is not especially large.

The primary remaining difficulty with hybrids is with mixing the propellants during the combustion process. In solid propellants, the oxidizer and fuel are mixed in a factory in carefully controlled conditions. Liquid propellants are generally mixed by the injector at the top of the combustion chamber, which directs many small swift-moving streams of fuel and oxidizer into one another. Liquid fuelled rocket injector design has been studied at great length and still resists reliable performance prediction. In a hybrid motor, the mixing happens at the melting or evaporating surface of the fuel. The mixing is not a well-controlled process and generally quite a lot of propellant is left

unburned, which limits the efficiency and thus the exhaust velocity of the motor. Additionally, as the burn continues, the hole down the center of the grain (the 'port') widens and the mixture ratio tends to become more oxidiser rich.

There has been much less development of hybrid motors than solid and liquid motors. For military use, ease of handling and maintenance have driven the use of solid rockets. For orbital work, liquid fuels are more efficient than hybrids and most development has concentrated there. There has recently been an increase in hybrid motor development for nonmilitary suborbital work:

- The Reaction Research Society (RRS), although known primarily for their work with liquid rocket propulsion, has a long history of research and development with hybrid rocket propulsion.

- Several universities have recently experimented with hybrid rockets. Brigham Young University, the University of Utah and Utah State University launched a student-designed rocket called Unity IV in 1995 which burned the solid fuel hydroxy-terminated polybutadiene (HTPB) with an oxidizer of gaseous oxygen, and in 2003 launched a larger version which burned HTPB with nitrous oxide.

- Portland State University also launched several hybrid rockets in the early 2000's.

- The Rochester Institute of Technology is currently creating a HTPB hybrid rocket to launch small payloads into space and to several near Earth objects. Its first launch is scheduled for Summer 2007. http://meteor.rit.edu

- Scaled Composites SpaceShipOne, the first private manned spacecraft, is powered by a hybrid rocket burning HTPB with nitrous oxide. The hybrid rocket engine was manufactured by SpaceDev. SpaceDev partially based its motors on experimental data collected from the testing of AMROC's (American Rocket Company) motors at NASA's Stennis Space Center's E1 test stand. Motors ranging from as small as 1000 lbf (4.4 kN) to as large as 250,000 lbf (1.1 MN) thrust were successfully tested. SpaceDev purchased AMROCs assets after the company was shut down for lack of funding.

Inert propellants

See also: ion drive

Some rocket designs have their propellants obtain their energy from non chemical or even external sources. For example water rockets use the compressed gas, typically air, to force the water out of the rocket.

Solar thermal rockets and Nuclear thermal rockets typically propose to use liquid hydrogen for an Isp of around 600-900 seconds, or in some cases water that is exhausted as steam for an Isp of about 190 seconds.

Additionally for low performance requirements such as attitude jets, inert gases such as nitrogen have been employed.

Mixture ratio

The theoretical exhaust velocity of a given propellant chemistry is a function of the energy released per unit of propellant mass (specific energy). Unburned fuel or oxidizer drags down the specific

energy. Surprisingly, most rockets run fuel-rich.

The usual explanation for fuel-rich mixtures is that fuel-rich mixtures have lower molecular weight exhaust, which by reducing M supposedly increases the ratio $\dfrac{\sqrt{T_c}}{M}$ which is approximately equal to the theoretical exhaust velocity. This explanation, though found in some textbooks, is wrong. Fuel-rich mixtures actually have lower theoretical exhaust velocities, because $\sqrt{T_c}$ decreases as fast or faster than M.

The nozzle of the rocket converts the thermal energy of the propellants into directed kinetic energy. This conversion happens in a short time, on the order of one millisecond. During the conversion, energy must transfer very quickly from the rotational and vibrational states of the exhaust molecules into translation. Molecules with fewer atoms (like CO and H_2) store less energy in vibration and rotation than molecules with more atoms (like CO_2 and H_2O). These smaller molecules transfer more of their rotational and vibrational energy to translation energy than larger molecules, and the resulting improvement in nozzle efficiency is large enough that real rocket engines improve their actual exhaust velocity by running rich mixtures with somewhat lower theoretical exhaust velocities.

The effect of exhaust molecular weight on nozzle efficiency is most important for nozzles operating near sea level. High expansion rockets operating in a vacuum see a much smaller effect, and so are run less rich. The Saturn-II stage (a LOX/LH$_2$ rocket) varied its mixture ratio during flight to optimize performance.

LOX/hydrocarbon rockets are run only somewhat rich (O/F mass ratio of 3 rather than stoichiometric of 3.4 to 4), because the energy release per unit mass drops off quickly as the mixture ratio deviates from stoichiometric. LOX/LH$_2$ rockets are run very rich (O/F mass ratio of 4 rather than stoichiometric 8) because hydrogen is so light that the energy release per unit mass of propellant drops very slowly with extra hydrogen. In fact, LOX/LH$_2$ rockets are generally limited in how rich they run by the performance penalty of the mass of the extra hydrogen tankage, rather than the mass of the hydrogen itself.

Another reason for running rich is that off-stoichiometric mixtures burn cooler than stoichiometric mixtures, which makes engine cooling easier. And as most engines are made of metal or carbon, hot oxidizer-rich exhaust is extremely corrosive, where fuel-rich exhaust is less so. American engines have all been fuel-rich. Some Soviet engines have been oxidizer-rich.

Additionally, there is a difference between mixture ratios for optimum specific impulse (I_{sp}) and optimum thrust. During launch, shortly after takeoff, high thrust is at a premium. This can be achieved at some temporary reduction of Isp by increasing the oxidiser ratio initially, and then transitioning to more fuel-rich mixtures. Since engine size is typically scaled for takeoff thrust this permits reduction of the weight of rocket engine, pipes and pumps and the extra propellant use can be more than compensated by increases of acceleration towards the end of the burn by having a reduced dry mass.

Propellant density

Although liquid hydrogen gives a high Isp, its low density is a significant disadvantage: hydrogen occupies about 7x more volume per kilogram than dense fuels such as kerosene. This not only penalises the tankage, but also the pipes and fuel pumps leading from the tank, which need to be 7x bigger and heavier. (The oxidiser side of the engine and tankage is of course unaffected.) This makes

the vehicle's dry mass much higher, so the use of liquid hydrogen is not such a big win as might be expected. Indeed, some dense hydrocarbon/LOX propellant combinations have higher performance when the dry mass penalties are included.

Due to lower Isp, dense propellant launch vehicles have a higher the vehicle may well end up cheaper. Liquid hydrogen is quite an expensive fuel to produce and store, and causes many practical difficulties with design and manufacture of the vehicle.

Because of the higher overall weight, a dense-fuelled launch vehicle necessarily requires higher takeoff thrust, but it carries this thrust capability all the way to orbit. This, in combination with the better thrust/weight ratios, means that dense-fuelled vehicles reach orbit earlier, thereby minimizing losses due to gravity drag. Thus, the effective delta-v requirement for these vehicles are reduced.

However, liquid hydrogen does give clear advantages when the overall mass needs to be minimised; for example the Saturn V vehicle used it on the upper stages; this reduced weight meant that the dense-fuelled first stage could be made proportionately smaller, saving quite a bit of money..

References

1. ^ ARBIT, H. A., CLAPP, S. D., DICKERSON, R. A., NAGAI, C. K., Combustion characteristics of the fluorine-lithium/hydrogen tripropellant combination. (http://www.aiaa.org/content.cfm?pageid=406&gTable=mtgpaper&gID=40999) AMERICAN INST OF AERONAUTICS AND ASTRONAUTICS, PROPULSION JOINT SPECIALIST CONFERENCE, 4TH, CLEVELAND, OHIO, Jun 10-14, 1968.

See also

- Category: Rocket fuels
- Comparison: Aviation fuel
- Nuclear propulsion
- Ion thruster

External links

- NASA page on propellants (http://www-pao.ksc.nasa.gov/kscpao/nasafact/count2.htm)
- History of solid rocket fuels (http://www.dfrc.nasa.gov/DTRS/1999/PDF/H-2330.pdf)
- Detailed list of rocket fuels, practical and theoretical (http://www.astronautix.com/props/index.htm)
- Rocket Man (http://3quarksdaily.blogs.com/3quarksdaily/2005/08/monday_musing_r.html) Short essay by S. Abbas Raza about development of solid rocket fuel at *3 Quarks Daily* (http://3quarksdaily/)

Retrieved from "http://en.wikipedia.org/wiki/Rocket_propellant"
Categories: Rocket propellants | Pyrotechnics | Spacecraft propulsion
Hidden categories: Articles lacking sources from March 2007 | All articles lacking sources | All articles with unsourced statements | Articles with unsourced statements since July 2007

Explosive material

From Wikipedia, the free encyclopedia
(Redirected from Explosive)

This article is concerned solely with chemical explosives. There are many other varieties of more exotic explosive material, and theoretical methods of causing explosions such as nuclear explosives and antimatter, and other methods of producing explosions, such as abrupt heating with a high-intensity laser or electric arc. For the compilation CD by the string quartet bond, see Explosive: The Best of bond.

An **explosive material** is a material that either is chemically or otherwise energetically unstable or produces a sudden expansion of the material usually accompanied by the production of heat and large changes in pressure (and typically also a flash and/or loud noise) upon initiation; this is called the explosion.

Contents

Chemical explosives

Explosives are classified as low or high explosives according to their rates of decomposition: low explosives burn rapidly (or deflagrate), while high explosives undergo detonations. No sharp distinction exists between low and high explosives, because of the difficulties inherent in precisely observing and measuring rapid decomposition.

The chemical decomposition of an explosive may take years, days, hours, or a fraction of a second. The slower processes of decomposition take place in storage and are of interest only from a stability standpoint. Of more interest are the two rapid forms of decomposition, deflagration and detonation.

The term "detonation" is used to describe an explosive phenomenon whereby the decomposition is propagated by the explosive shockwave traversing the explosive material. The shockwave front is capable of passing through the high explosive material at great speeds, typically thousands of meters per second.

Explosives usually have less potential energy than petroleum fuels, but their high rate of energy release produces the great blast pressure. TNT has a detonation velocity of 6,940 m/s compared to 1,680 m/s for the detonation of a pentane-air mixture, and the 0.34-m/s stoichiometric flame speed of gasoline combustion in air.

Explosive force is released in a direction perpendicular to the surface of the explosive. If the surface is cut or shaped, the explosive forces can be focused to produce a greater local effect; this is known as a shaped charge.

In a low explosive, the decomposition is propagated by a flame front which travels much more slowly through the explosive material.

The properties of the explosive indicate the class into which it falls. In some cases explosives can be made to fall into either class by the conditions under which they are initiated. In sufficiently massive quantities, almost all low explosives can undergo a Deflagration to Detonation Transition (DDT). For convenience, low and high explosives may be differentiated by the shipping and storage classes.

Explosive compatibility groupings

Shipping labels and tags will include UN and national, e.g. USDOT, hazardous material Class with Compatibility Letter, as follows:

- **1.1** Mass Explosion Hazard
- **1.2** Non-mass explosion, fragment-producing
- **1.3** Mass fire, minor blast or fragment hazard
- **1.4** Moderate fire, no blast or fragment: a consumer firework is 1.4G or 1.4S
- **1.5** Explosive substance, very insensitive (with a mass explosion hazard)
- **1.6** Explosive article, extremely insensitive

Explosives warning sign
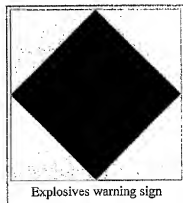
A Primary explosive substance (1.1A)

B An article containing a primary explosive substance and not containing two or more effective

protective features. Some articles, such as detonator assemblies for blasting and primers, cap-type, are included. (1.1B, 1.2B, 1.4B)

C Propellant explosive substance or other deflagrating explosive substance or article containing such explosive substance (1.1C, 1.2C, 1.3C, 1.4C)

D Secondary detonating explosive substance or black powder or article containing a secondary detonating explosive substance, in each case without means of initiation and without a propelling charge, or article containing a primary explosive substance and containing two or more effective protective features. (1.1D, 1.2D, 1.4D, 1.5D)

E Article containing a secondary detonating explosive substance without means of initiation, with a propelling charge (other than one containing flammable liquid, gel or hypergolic liquid) (1.1E, 1.2E, 1.4E)

F containing a secondary detonating explosive substance with its means of initiation, with a propelling charge (other than one containing flammable liquid, gel or hypergolic liquid) or without a propelling charge (1.1F, 1.2F, 1.3F, 1.4F)

G Pyrotechnic substance or article containing a pyrotechnic substance, or article containing both an explosive substance and an illuminating, incendiary, tear-producing or smoke-producing substance (other than a water-activated article or one containing white phosphorus, phosphide or flammable liquid or gel or hypergolic liquid) (1.1G, 1.2G, 1.3G, 1.4G)

H Article containing both an explosive substance and white phosphorus (1.2H, 1.3H)

J Article containing both an explosive substance and flammable liquid or gel (1.1J, 1.2J, 1.3J)

K Article containing both an explosive substance and a toxic chemical agent (1.2K, 1.3K)

L Explosive substance or article containing an explosive substance and presenting a special risk (e.g., due to water-activation or presence of hypergolic liquids, phosphides or pyrophoric substances) needing isolation of each type (1.1L, 1.2L, 1.3L)

N Articles containing only extremely insensitive detonating substances (1.6N)

S Substance or article so packed or designed that any hazardous effects arising from accidental functioning are limited to the extent that they do not significantly hinder or prohibit fire fighting or other emergency response efforts in the immediate vicinity of the package (1.4S)

Low explosives

A **low explosive** is usually a mixture of a combustible substance and an oxidant that decomposes rapidly (deflagration); unlike most high explosives, which are compounds.

Under normal conditions, low explosives undergo deflagration at rates that vary from a few centimeters per second to approximately 400 metres per second. However, it is possible for them to deflagrate very quickly, producing an effect similar to a detonation, but not an actual detonation; This usually occurs when ignited in a confined space.

Low explosives are normally employed as propellants. Included in this group are gun powders and pyrotechnics such as flares and illumination devices.

High explosives

High explosives are normally employed in mining, demolition, and military warheads. They undergo detonation at rates of 1,000 to 9,000 meters per second. High explosives are conventionally subdivided into two classes differentiated by sensitivity:

- **Primary explosives** are extremely sensitive to mechanical shock, friction, and heat, to which they will respond by burning rapidly or detonating.
- **Secondary explosives**, also called **base explosives**, are relatively insensitive to shock, friction, and heat. They may burn when exposed to heat or flame in small, unconfined quantities, but detonation can occur. These are sometimes added in small amounts to blasting caps to boost their power. Dynamite, TNT, RDX, PETN, HMX, and others are secondary explosives. PETN is often considered a benchmark compound, with materials that are more sensitive than PETN being classified as primary explosives.

Some definitions add a third category:

- **Tertiary explosives**, also called **blasting agents**, are so insensitive to shock that they cannot be reliably detonated by practical quantities of primary explosive, and instead require an intermediate explosive booster of secondary explosive. Examples include an ammonium nitrate/fuel oil mixture (ANFO) and slurry or "wet bag" explosives. These are primarily used in large-scale mining and construction operations.

Note that many if not most explosive chemical compounds may usefully deflagrate as well as detonate, and are used in high as well as low explosive compositions. This also means that under extreme conditions, a propellant can detonate. For example, nitrocellulose deflagrates if ignited, but detonates if initiated by a detonator.

Detonation of an explosive charge

The **explosive train**, also called an **initiation sequence** or **firing train,** is the sequence of charges that progresses from relatively low levels of energy to initiate the final explosive material or main charge. There are low- and high-explosive trains. Low-explosive trains are as simple as a rifle cartridge, including a primer and a propellant charge. High-explosives trains can be more complex, either two-step (e.g., detonator and dynamite) or three-step (e.g., detonator, booster of primary explosive, and main charge of secondary explosive). Detonators are often made from tetryl and fulminates.

Composition of the material

An explosive may consist of either a chemically pure compound, such as nitroglycerin, or a mixture of an oxidizer and a fuel, such as black powder.

Mixtures of an oxidizer and a fuel

An oxidizer is a pure substance (molecule) that in a chemical reaction can contribute some atoms of one or more oxidizing elements, in which the fuel component of the explosive burns. On the simplest level, the oxidizer may itself be an oxidizing element, such as gaseous or liquid oxygen.

- **Black powder:** Potassium nitrate, charcoal and sulfur

- **Flash powder:** Fine metal powder (usually aluminium or magnesium) and a strong oxidizer (e.g. potassium chlorate or perchlorate).
- **Ammonal:** Ammonium nitrate and aluminium powder.
- **Armstrong's mixture:** Potassium chlorate and red phosphorus. This is a very sensitive mixture. It is a primary high explosive in which sulfur is substituted for some or all phosphorus to slightly decrease sensitivity.
- **Sprengel explosives:** A very general class incorporating any strong oxidizer and highly reactive fuel, although in practice the name most commonly was applied to mixtures of chlorates and nitroaromatics.
  - **ANFO:** Ammonium nitrate and fuel oil.
  - **Cheddites:** Chlorates or perchlorates and oil.
  - **Oxyliquits:** Mixtures of organic materials and liquid oxygen.
  - **Panclastites:** Mixtures of organic materials and dinitrogen tetroxide.

Chemically pure compounds

Some chemical compounds are unstable in that, when shocked, they react, possibly to the point of detonation. Each molecule of the compound dissociates into two or more new molecules (generally gases) with the release of energy.

- **Nitroglycerin:** A highly unstable and sensitive liquid.
- **Acetone peroxide:** A very unstable white organic peroxide
- **TNT:** Yellow insensitive crystals that can be melted and cast without detonation.
- **Nitrocellulose:** A nitrated polymer which can be a high or low explosive depending on nitration level and conditions.
- **RDX, PETN, HMX:** Very powerful explosives which can be used pure or in plastic explosives.
  - **C-4 (or Composition C-4):** An RDX plastic explosive plasticized to be adhesive and malleable.

The above compositions may describe the majority of the explosive material, but a practical explosive will often include small percentages of other materials. For example, dynamite is a mixture of highly sensitive nitroglycerin with sawdust, powdered silica, or most commonly diatomaceous earth, which act as stabilizers. Plastics and polymers may be added to bind powders of explosive compounds; waxes may be incorporated to make them safer to handle; aluminum powder may be introduced to increase total energy and blast effects. Explosive compounds are also often "alloyed": HMX or RDX powders may be mixed (typically by melt-casting) with TNT to form Octol or Cyclotol.

Chemical explosive reaction

A chemical explosive is a compound or mixture which, upon the application of heat or shock, decomposes or rearranges with extreme rapidity, yielding much gas and heat. Many substances not ordinarily classed as explosives may do one, or even two, of these things. For example, at high temperatures (> 2000°C) a mixture of nitrogen and oxygen can be made to react with great rapidity and yield the gaseous product nitric oxide; yet the mixture is not an explosive since it does not evolve heat, but rather absorbs heat.

$$N_2 + O_2 \rightarrow 2NO - 43{,}200 \text{ calories (or 180 kJ) per mole of } N_2$$
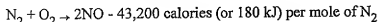
For a chemical to be an explosive, it must exhibit all of the following:

- Rapid expansion (i.e.,. rapid production of gases or rapid heating of surroundings)
- Evolution of heat
- Rapidity of reaction
- Initiation of reaction

Evolution of heat

The generation of heat in large quantities accompanies every explosive chemical reaction. It is this rapid liberation of heat that causes the gaseous products of reaction to expand and generate high pressures. This rapid generation of high pressures of the released gas constitutes the explosion. It should be noted that the liberation of heat with insufficient rapidity will not cause an explosion. For example, although a pound of coal yields five times as much heat as a pound of nitroglycerin, the coal cannot be used as an explosive because the rate at which it yields this heat is quite slow.

Rapidity of reaction

Rapidity of reaction distinguishes the explosive reaction from an ordinary combustion reaction by the great speed with which it takes place. Unless the reaction occurs rapidly, the thermally expanded gases will be dissipated in the medium, and there will be no explosion. Again, consider a wood or coal fire. As the fire burns, there is the evolution of heat and the formation of gases, but neither is liberated rapidly enough to cause an explosion. This can be likened to the difference between the energy discharge of a battery, which is slow, and that of a flash capacitor like that in a camera flash, which releases its energy all at once.

Initiation of reaction

A reaction must be capable of being initiated by the application of shock or heat to a small portion of the mass of the explosive material. A material in which the first three factors exist cannot be accepted as an explosive unless the reaction can be made to occur when desired.

Sensitiser

A sensitiser is a powdered or fine particulate material that is sometimes used to create voids that aid in the initiation or propagation of the detonation wave. [1] (http://cms.3m.com/cms/US/en/2-68/czrzrFE/view.jhtml) It may be as high-tech as glass beads (Glass Bubbles[2] (http://cms.3m.com/cms/US/en/2-68/czrzrFE/view.jhtml)) or as simple as black cumin seeds[3] (http://webarchive.unionleader.com/articles_showa.html?article=61637).

Military explosives

To determine the suitability of an explosive substance for military use, its physical properties must first be investigated. The usefulness of a military explosive can only be appreciated when these properties and the factors affecting them are fully understood. Many explosives have been studied in past years to determine their suitability for military use and most have been found wanting. Several of those found acceptable have displayed certain characteristics that are considered undesirable and, therefore, limit their usefulness in military applications. The requirements of a military explosive are stringent, and very few explosives display all of the characteristics necessary to make them acceptable for military standardization. Some of the more important characteristics are discussed below:

Availability and cost

In view of the enormous quantity demands of modern warfare, explosives must be produced from cheap raw materials that are nonstrategic and available in great quantity. In addition, manufacturing operations must be reasonably simple, cheap, and safe.

Sensitivity

Regarding an explosive, this refers to the ease with which it can be ignited or detonated—i.e., the amount and intensity of shock, friction, or heat that is required. When the term sensitivity is used, care must be taken to clarify what kind of sensitivity is under discussion. The relative sensitivity of a given explosive to impact may vary greatly from its sensitivity to friction or heat. Some of the test methods used to determine sensitivity are as follows:

- **Impact** Sensitivity is expressed in terms of the distance through which a standard weight must be dropped to cause the material to explode.
- **Friction** Sensitivity is expressed in terms of what occurs when a weighted pendulum scrapes across the material (snaps, crackles, ignites, and/or explodes).
- **Heat** Sensitivity is expressed in terms of the temperature at which flashing or explosion of the material occurs.

Sensitivity is an important consideration in selecting an explosive for a particular purpose. The explosive in an armor-piercing projectile must be relatively insensitive, or the shock of impact would cause it to detonate before it penetrated to the point desired. The explosive lenses around nuclear charges are also designed to be highly insensitive, to minimize the risk of accidental detonation.

Stability

Stability is the ability of an explosive to be stored without deterioration.

The following factors affect the stability of an explosive:

- **Chemical constitution.** The very fact that some common chemical compounds can undergo explosion when heated indicates that there is something unstable in their structures. While no precise explanation has been developed for this, it is generally recognized that certain radical groups, nitrite ($-NO_2$), nitrate ($-NO_3$), and azide ($-N_3$), are intrinsically in a condition of internal strain. Increasing the strain by heating can cause a sudden disruption of the molecule and consequent explosion. In some cases, this condition of molecular instability is so great that decomposition takes place at ordinary temperatures.
- **Temperature of storage.** The rate of decomposition of explosives increases at higher temperatures. All of the standard military explosives may be considered to have a high degree of stability at temperatures of -10 to +35 °C, but each has a high temperature at which the rate of decomposition rapidly accelerates and stability is reduced. As a rule of thumb, most explosives become dangerously unstable at temperatures exceeding 70 °C.
- **Exposure to the sun.** If exposed to the ultraviolet rays of the sun, many explosive compounds that contain nitrogen groups will rapidly decompose, affecting their stability.
- **Electrical discharge.** Electrostatic or spark sensitivity to initiation is common to a number of explosives. Static or other electrical discharge may be sufficient to inspire detonation under some circumstances. As a result, the safe handling of explosives and pyrotechnics almost always requires electrical grounding of the operator.

Power

The term "power" (or more properly, performance) as applied to an explosive refers to its ability to do work. In practice it is defined as the explosive's ability to accomplish what is intended in the way of energy delivery (i.e., fragment projection, air blast, high-velocity jets, underwater shock and bubble energy, etc.). Explosive power or performance is evaluated by a tailored series of tests to assess the material for its intended use. Of the tests listed below, cylinder expansion and air-blast tests are common to most testing programs, and the others support specific applications.

- **Cylinder expansion test.** A standard amount of explosive is loaded into a long hollow cylinder, usually of copper, and detonated at one end. Data is collected concerning the rate of radial expansion of the cylinder and maximum cylinder wall velocity. This also establishes the Gurney energy or $2E$.
- **Cylinder fragmentation.** A standard steel cylinder is loaded with explosive and detonated in a sawdust pit. The fragments are collected and the size distribution analyzed.
- **Detonation pressure (Chapman-Jouguet condition).** Detonation pressure data derived from measurements of shock waves transmitted into water by the detonation of cylindrical explosive charges of a standard size.
- **Determination of critical diameter.** This test establishes the minimum physical size a charge of a specific explosive must be to sustain its own detonation wave. The procedure involves the detonation of a series of charges of different diameters until difficulty in detonation wave propagation is observed.
- **Infinite-diameter detonation velocity.** Detonation velocity is dependent on loading density (c), charge diameter, and grain size. The hydrodynamic theory of detonation used in predicting explosive phenomena does not include diameter of the charge, and therefore a detonation velocity, for an imaginary charge of Infinite diameter. This procedure requires a series of charges of the same density and physical structure, but different diameters, to be fired and the resulting detonation velocities extrapolated to predict the detonation velocity of a charge of infinite diameter.
- **Pressure versus scaled distance.** A charge of specific size is detonated and its pressure effects measured at a standard distance. The values obtained are compared with that for TNT.
- **Impulse versus scaled distance.** A charge of specific size is detonated and its impulse (the area under the pressure-time curve) measured versus distance. The results are tabulated and expressed in TNT equivalent.
- **Relative bubble energy (RBE).** A 5- to 50-kg charge is detonated in water and piezoelectric gauges measure peak pressure, time constant, impulse, and energy.

> The RBE may be defined as $K_x\ 3$
>
> RBE $= K_s$
>
> where K = bubble expansion period for experimental (x) or standard (s) charge.

Brisance

In addition to strength, explosives display a second characteristic, which is their shattering effect or brisance (from the French meaning to "break"), which is distinguished from their total work capacity. An exploding propane tank may release more chemical energy than an ounce of nitroglycerin, but the tank would probably fragment into large pieces of twisted metal, while a metal casing around the nitroglycerin would be pulverized. This characteristic is of practical importance in determining the effectiveness of an explosion in fragmenting shells, bomb casings, grenades, and the like. The rapidity with which an explosive reaches its peak pressure is a measure of its brisance. Brisance values are primarily employed in France and Russia.

The sand crush test is commonly employed to determine the relative brisance in comparison to TNT. No test is capable of directly comparing the explosive properties of two or more compounds; it is important to examine the data from several such tests (sand crush, trauzl, and so forth) in order to gauge relative brisance. True values for comparison will require field experiments.

Density

Density of loading refers to the mass of an explosive per unit volume. Several methods of loading are available, including pellet loading, cast loading, and press loading; the one used is determined by the characteristics of the explosive. Dependent upon the method employed, an average density of the loaded charge can be obtained that is within 80-99% of the theoretical maximum density of the explosive. High load density can reduce sensitivity by making the mass more resistant to internal friction. However, if density is increased to the extent that individual crystals are crushed, the explosive may become more sensitive. Increased load density also permits the use of more explosive, thereby increasing the power of the warhead. It is possible to compress an explosive beyond a point of sensitivity, known also as "dead-pressing," in which the material is no longer capable of being reliably initiated, if at all.

Volatility

Volatility, or the readiness with which a substance vaporizes, is an undesirable characteristic in military explosives. Explosives must be no more than slightly volatile at the temperature at which they are loaded or at their highest storage temperature. Excessive volatility often results in the development of pressure within rounds of ammunition and separation of mixtures into their constituents. Stability, as mentioned before, is the ability of an explosive to stand up under storage conditions without deteriorating. Volatility affects the chemical composition of the explosive such that a marked reduction in stability may occur, which results in an increase in the danger of handling. Maximum allowable volatility is 2 ml of gas evolved in 48 hours.

Hygroscopicity

The introduction of water into an explosive is highly undesirable since it reduces the sensitivity, strength, and velocity of detonation of the explosive. Hygroscopicity is used as a measure of a material's moisture-absorbing tendencies. Moisture affects explosives adversely by acting as an inert material that absorbs heat when vaporized, and by acting as a solvent medium that can cause undesired chemical reactions. Sensitivity, strength, and velocity of detonation are reduced by inert materials that reduce the continuity of the explosive mass. When the moisture content evaporates during detonation, cooling occurs, which reduces the temperature of reaction. Stability is also affected by the presence of moisture since moisture promotes decomposition of the explosive and, in addition, causes corrosion of the explosive's metal container. For all of these reasons, hygroscopicity must be negligible in military explosives.

Toxicity

Due to their chemical structure, most explosives are toxic to some extent. Since the toxic effect may vary from a mild headache to serious damage of internal organs, care must be taken to limit toxicity in military explosives to a minimum. Any explosive of high toxicity is unacceptable for military use. Explosive product gases can also be toxic.

Measurement of chemical explosive reaction

The development of new and improved types of ammunition requires a continuous program of research and development. Adoption of an explosive for a particular use is based upon both proving ground and service tests. Before these tests, however, preliminary estimates of the characteristics of the explosive are made. The principles of thermochemistry are applied for this process.

Thermochemistry is concerned with the changes in internal energy, principally as heat, in chemical reactions. An explosion consists of a series of reactions, highly exothermic, involving decomposition of the ingredients and recombination to form the products of explosion. Energy changes in explosive reactions are calculated either from known chemical laws or by analysis of the products.

For most common reactions, tables based on previous investigations permit rapid calculation of energy changes. Products of an explosive remaining in a closed calorimetric bomb (a constant-volume explosion) after cooling the bomb back to room temperature and pressure are rarely those present at the instant of maximum temperature and pressure. Since only the final products may be analyzed conveniently, indirect or theoretical methods are often used to determine the maximum temperature and pressure values.

Some of the important characteristics of an explosive that can be determined by such theoretical computations are:

- Oxygen balance
- Heat of explosion or reaction
- Volume of products of explosion
- Potential of the explosive

Oxygen balance (OB%)

Oxygen balance is an expression that is used to indicate the degree to which an explosive can be oxidized. If an explosive molecule contains just enough oxygen to convert all of its carbon to carbon dioxide, all of its hydrogen to water, and all of its metal to metal oxide with no excess, the molecule is said to have a zero oxygen balance. The molecule is said to have a positive oxygen balance if it contains more oxygen than is needed and a negative oxygen balance if it contains less oxygen than is needed. The sensitivity, strength, and brisance of an explosive are all somewhat dependent upon oxygen balance and tend to approach their maximums as oxygen balance approaches zero.

Heat of explosion

When a chemical compound is formed from its constituents, heat may either be absorbed or released. The quantity of heat absorbed or given off during transformation is called the heat of formation. Heats of formations for solids and gases found in explosive reactions have been determined for a temperature of 15 °C and atmospheric pressure, and are normally given in units of kilocalories per gram-molecule. (See table 12-1). A negative value indicates that heat is absorbed during the formation of the compound from its elements; such a reaction is called an endothermic reaction.

The arbitrary convention usually employed in simple thermochemical calculations is to take heat contents of all elements as zero in their standard states at all temperatures (standard state being defined as natural or ambient conditions). Since the heat of formation of a compound is the net difference between the heat content of the compound and that of its elements, and since the latter are taken as zero by convention, it follows that the heat content of a compound is equal to its heat of formation in such non-rigorous calculations. This leads to the principle of initial and final state, which may be expressed as follows: "The net quantity of heat liberated or absorbed in any chemical

modification of a system depends solely upon the initial and final states of the system, provided the transformation takes place at constant volume or at constant pressure. It is completely independent of the intermediate transformations and of the time required for the reactions." From this it follows that the heat liberated in any transformation accomplished through successive reactions is the algebraic sum of the heats liberated or absorbed in the several reactions. Consider the formation of the original explosive from its elements as an intermediate reaction in the formation of the products of explosion. The net amount of heat liberated during an explosion is the sum of the heats of formation of the products of explosion, minus the heat of formation of the original explosive. The net difference between heats of formations of the reactants and products in a chemical reaction is termed the heat of reaction. For oxidation this heat of reaction may be termed heat of combustion.

In explosive technology only materials that are exothermic—that have a heat of reaction that causes net liberation of heat—are of interest. Hence, in this context, virtually all heats of reaction are positive. Reaction heat is measured under conditions either of constant pressure or constant volume. It is this heat of reaction that may be properly expressed as the "heat of explosion."

Balancing chemical explosion equations

In order to assist in balancing chemical equations, an order of priorities is presented in table 12-1. Explosives containing C, H, O, and N and/or a metal will form the products of reaction in the priority sequence shown. Some observation you might want to make as you balance an equation:

- The progression is from top to bottom; you may skip steps that are not applicable, but you never back up.
- At each separate step there are never more than two compositions and two products.
- At the conclusion of the balancing, elemental nitrogen, oxygen, and hydrogen are always found in diatomic form.

Table 12-1. Order of Priorities

Priority	Composition of explosive	Products of decomposition	Phase of products
1	A metal and chlorine	Metallic chloride	Solid
2	Hydrogen and chlorine	HCl	Gas
3	A metal and oxygen	Metallic oxide	Solid
4	Carbon and oxygen	CO	Gas
5	Hydrogen and oxygen	H_2O	Gas
6	Carbon monoxide and oxygen	CO_2	Gas
7	Nitrogen	N_2	Gas
8	Excess oxygen	O_2	Gas
9	Excess hydrogen	H_2	Gas

Example, TNT:

$C_6H_2(NO_2)_3CH_3$; constituents: $7C + 5H + 3N + 6O$
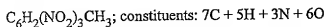
Using the order of priorities in table 12-1, priority 4 gives the first reaction products:

$$7C + 6O \rightarrow 6CO \text{ with one mol of carbon remaining}$$
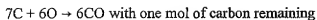
Next, since all the oxygen has been combined with the carbon to form CO, priority 7 results in:

$$3N \rightarrow 1.5N_2$$

Finally, priority 9 results in: $5H \rightarrow 2.5H_2$

The balanced equation, showing the products of reaction resulting from the detonation of TNT is:

$$C_6H_2(NO_2)_3CH_3 \rightarrow 6CO + 2.5H_2 + 1.5N_2 + C$$

Notice that partial moles are permitted in these calculations. The number of moles of gas formed is 10. The product carbon is a solid.

Volume of products of explosion

The law of Avogadro states that equal volumes of all gases under the same conditions of temperature and pressure contain the same number of molecules, that is, the molar volume of one gas is equal to the molar volume of any other gas. The molar volume of any gas at 0°C and under normal atmospheric pressure is very nearly 22.4 liters. Thus, considering the nitroglycerin reaction,

$$C_3H_5(NO_3)_3 \rightarrow 3CO_2 + 2.5H_2O + 1.5N_2 + 0.25O_2$$
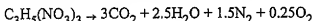
the explosion of one mole of nitroglycerin produces 3 moles of CO_2, 2.5 moles of H_2O, 1.5 moles of N_2, and 0.25 mole of O_2, all in the gaseous state. Since a molar volume is the volume of one mole of gas, one mole of nitroglycerin produces $3 + 2.5 + 1.5 + 0.25 = 7.25$ molar volumes of gas; and these molar volumes at 0°C and atmospheric pressure form an actual volume of $7.25 \times 22.4 = 162.4$ liters of gas.

Based upon this simple beginning, it can be seen that the volume of the products of explosion can be predicted for any quantity of the explosive. Further, by employing Charles' Law for perfect gases, the volume of the products of explosion may also be calculated for any given temperature. This law states that at a constant pressure a perfect gas expands 1/273.15 of its volume at 0 °C, for each degree Celsius of rise in temperature.

Therefore, at 15 °C (288.15 kelvin) the molar volume of an ideal gas is

$$V_{15} = 22.414 \ (288.15/273.15) = 23.64 \text{ liters per mole}$$

Thus, at 15 °C the volume of gas produced by the explosive decomposition of one mole of nitroglycerin becomes

$$V = (23.64 \text{ l/mol})(7.25 \text{ mol}) = 171.4 \text{ l}$$

Explosive strength

The *potential* of an explosive is the total work that can be performed by the gas resulting from its explosion, when expanded adiabatically from its original volume, until its pressure is reduced to atmospheric pressure and its temperature to 15 °C. The potential is therefore the total quantity of

heat given off at constant volume when expressed in equivalent work units and is a measure of the strength of the explosive.
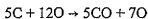
Example of thermochemical calculations

The PETN reaction will be examined as an example of thermo-chemical calculations.
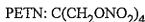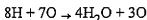
PETN: $C(CH_2ONO_2)_4$
Molecular weight = 316.15 g/mol
Heat of formation = 119.4 kcal/mol

(1) Balance the chemical reaction equation. Using table 12-1, priority 4 gives the first reaction products:

$$5C + 12O \rightarrow 5CO + 7O$$

Next, the hydrogen combines with remaining oxygen:

$$8H + 7O \rightarrow 4H_2O + 3O$$

Then the remaining oxygen will combine with the CO to form CO and CO_2.

$$5CO + 3O \rightarrow 2CO + 3CO_2$$
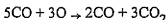
Finally the remaining nitrogen forms in its natural state (N_2).

$$4N \rightarrow 2N_2$$

The balanced reaction equation is:

$$C(CH_2ONO_2)_4 \rightarrow 2CO + 4H_2O + 3CO_2 + 2N_2$$
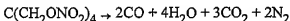
(2) Determine the number of molar volumes of gas per mole. Since the molar volume of one gas is equal to the molar volume of any other gas, and since all the products of the PETN reaction are gaseous, the resulting number of molar volumes of gas (N_m) is:

$$N_m = 2 + 4 + 3 + 2 = 11 \ V_{molar}/mol$$

(3) Determine the potential (capacity for doing work). If the total heat liberated by an explosive under constant volume conditions (Q_m) is converted to the equivalent work units, the result is the potential of that explosive.

The heat liberated at constant volume (Q_{mv}) is equivalent to the liberated at constant pressure (Q_{mp}) plus that heat converted to work in expanding the surrounding medium. Hence, $Q_{mv} = Q_{mp} +$ work (converted).

    a. $Q_{mp} = Q_{fi}$ (products) - Q_{fk} (reactants)

        where: Q_f = heat of formation (see table 12-1)

For the PETN reaction:

$$Q_{mp} = 2(26.343) + 4(57.81) + 3(94.39) - (119.4) = 447.87 \text{ kcal/mol}$$

(If the compound produced a metallic oxide, that heat of formation would be included in Q_{mp}.)

b. Work = $0.572 N_m = 0.572(11) = 6.292$ kcal/mol

As previously stated, Q_{mv} converted to equivalent work units is taken as the potential of the explosive.

c. Potential $J = Q_{mv}$ (4.185 × 10^6 kg)(MW) = 454.16 (4.185 × 10^6) 316.15 = 6.01 × 10^6 J kg

This product may then be used to find the relative strength (RS) of PETN, which is

d. RS = Pot (PETN) = 6.01 × 10^6 = 2.21 Pot (TNT) 2.72 × 10^6

See also

- Explosives used during WW II
- Nuclear weapon
- Weapon
- Explosive velocity
- Binary explosive
- Explosives safety
- Pressure pulse
- Energetically unstable

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- Swiss Agency for the Environment, Forests, and Landscap. 'Occurrence and relevance of organic pollutants in compost, digestate and organic residues', *Research for Agriculture and Nature*. 8 November 2004. p 52, 91, 182.

External links

- Blaster Exchange - Explosives Industry Portal (http://www.blasterexchange.com/)
- Explosive information and guides (http://www.wikipyro.com/)
- Why high nitrogen density in explosives? (http://www.newton.dep.anl.gov/askasci/chem99/chem99306.htm)
- The Explosives and Weapons Forum (http://www.roguesci.org/theforum)

- Military Explosives (http://www.fas.org/man/dod-101/navy/docs/fun/part12.htm)
- UN hazard classification code
  (http://globalsecurity.org/military/systems/munitions/explosives-class.htm)
- Class 1 Hazmat Placards
  (http://environmentalchemistry.com/yogi/hazmat/placards/class1.html)
- Journal of Energetic Materials (http://www.tandf.co.uk/journals/titles/07370652.asp)

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